

Classification of Fault Clearing Strategies for HVDC Grids

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SUMMARY

This paper defines and classifies fault clearing strategies for HVDC grid protection, based on the method of fault current interruption. HVDC grid protection must act on a much shorter timescale than AC grid protection and faces the challenge to interrupt fast rising fault currents without natural zero crossings. Conversely, the HVDC grid protection equipment, such as HVDC breakers or converters with fault blocking capability, offers several degrees of freedom for fault clearing strategies for HVDC grid protection. However, each of these strategies fulfils different objectives and imposes different requirements on HVDC grid components. Therefore, a classification of fault clearing strategies is needed. In this paper, the objectives and requirements for HVDC grid protection are described. Furthermore, constraints on HVDC grid protection are given. Available methods for fault current interruption and protective relaying algorithms are briefly reviewed. Different classes of fault clearing strategies are defined and the options for fault current interruption and protective relaying algorithm for each strategy are given.

KEYWORDS

Fault Clearing Strategy, HVDC Grid, Power System Protection, Power System Fault

1. INTRODUCTION

HVDC grid protection differs from ac grid protection due to the different nature of short circuit phenomena. First, the DC fault current has no natural zero crossings, which implies the use of different methods for fault current interruption 1. Second, the DC fault current rises to a high steady-state value, whereas power electronic equipment has only limited overcurrent withstand capabilities. Consequently, the HVDC grid protection must act faster than current AC grid protection 2.

The fault clearing strategy fundamentally determines the HVDC grid protection equipment and implementation. In addition, the fault clearing strategy depends on the objectives that are set for the HVDC grid protection. In the literature, several options for fault clearing in HVDC grids have been proposed. First, in 3-5, selective protection comparable to AC system protection is proposed, which implies the use of fast breakers at each transmission line end and a selective relaying algorithm. Second, in 6 the HVDC grid is split into different sub-grids, which are separated by fast breakers. Third, in 7 and 8, the DC fault is first cleared by first opening all breakers in the network and thereafter reclosing the breakers at the healthy lines. Fourth, in 9, low speed HVDC grid protection is proposed, which requires fault tolerant HVDC converters. Fifth, in 10, the DC fault current is interrupted by opening the AC circuit breakers of all converters, after which DC disconnectors isolate the faulted section of the HVDC grid. Each of these options fulfils different objectives and imposes different requirements on the HVDC grid protection equipment and components. Furthermore, these

strategies differ in their impact on the HVDC grid and AC grid during fault clearing and post-fault recovery.

This paper defines and classifies fault clearing strategies for HVDC grids, based on method of fault current interruption and fault clearing time. First, the HVDC grid protection objectives and requirements are discussed in Section 2. Thereafter, constraints on the fault clearing time are described in Section 3. A brief discussion on HVDC grid protection equipment and protective relaying algorithms is given in Section 4. Then, the fault clearing strategies are defined and described in Section 5. Finally, conclusions are stated in Section 6.

2. HVDC GRID PROTECTION OBJECTIVES AND REQUIREMENTS

This Section describes the HVDC grid protection objectives and the requirements they impose on the protection system.

2.1. Objectives of HVDC Grid Protection

Similar to AC grids, the HVDC grid will be affected by a variety of faults. Therefore, a fault clearing strategy is needed to minimize the negative effect of these faults on the system aspects such as stability and reliability. The objectives of the HVDC grid protection are similar to those of AC protection [1]:

1. Ensure human safety

An essential task of the protection system is to ensure human safety by fast isolation of the faults in the related equipment such as DC transmission lines, buses or DC substation converter transformers. A fault that persists for a longer time not only damages HVDC grid system equipment but also poses hazards to the surrounding areas due to creation of electro-magnetic fields.

2. Minimize fault impact on the grid

First, DC side faults disturb the normal operation of the HVDC grid. To ensure the reliability of the HVDC grid, the protection system should minimize the section of the HVDC grid that is disconnected after a fault occurs. The extent of a disturbance after a fault in the HVDC grid depends on the speed of fault current interruption and the protective algorithm. The slower the fault is cleared, the further the fault has propagated in the HVDC grid. Second, as a HVDC grid will be used for bulk transport of power, outage of a large part of the HVDC grid might cause problems to the underlying AC system. Hence, the HVDC grid protection must also limit the impact of a DC side fault on the AC grid.

3. Minimize stress to components

Besides the protection of the grid, damage to components should be avoided as this can shorten their lifetime. Therefore, in case of faults, the HVDC grid protection system must minimize the stress to its components.

2.2. HVDC Grid Protection Requirements

The objectives of protection for a grid can be translated into a philosophy for the protection system, meeting following requirements [2]:

- **Reliability:** Reliability of the protection system includes dependability and security. Dependability implies the correct action of the protection system against faults that need action. Security implies the non-action of the protection system in cases when the protection

system must not act [4]. Especially when considering large protection zones, in which large sections are isolated in case of a fault, security is important.

- **Speed:** The protection system must act fast to avoid damage to equipment, limit the fault current within the maximum interruptible current and limit the impact of the disturbance on the network. In the DC grid, time constraints are extremely stringent, typically in the order of milliseconds.
- **Sensitivity:** Every faulty situation must be detected and cleared.
- **Selectivity:** The protection system must define zones of protection which are separated by selectivity criteria in the fault detection. Only the zone that contains the fault should be isolated.
- **Robustness:** The protection system must be able to operate even in degraded situations. Duplication of protection systems to provide redundancy can aid to robustness.
- **Stability:** After fault clearance, the system must reach stable operation within an acceptable time period.

These objectives and requirements of DC protection are in principle similar as for traditional AC systems. However, the constraints within which the protection system must act, differ significantly.

3. HVDC GRID PROTECTION CONSTRAINTS

Constraints for HVDC grid protection can be imposed either at the DC or AC side. They can be situated at component or system level. Below, these constraints are consecutively discussed for the DC as well as the AC side.

3.1. DC Side Constraints

First, the limited overcurrent capability of power electronics puts a constraint on the time available for fault clearing. IGBTs have a limited range of currents and voltages that they can safely turn off, characterized by the Safe Operating Area (SOA). Typically, the maximum current that can be turned off is twice the continuous conducting current. Diodes or thyristors can withstand higher currents, characterized by the surge current withstand capability [12]. The constraints imposed by the power electronics can be situated at the HVDC converter or at the HVDC breaker (if based on power electronics).

The converters must block their IGBTs before the maximum current that they can safely turn off, is exceeded. On the one hand, if the converter topology is of the non-fault blocking type (e.g. half-bridge Modular Multilevel Converter (MMC)), the current is commutated to the IGBT anti-parallel diodes and fed by the AC side [13]. From that moment, the time for fault clearance is limited by the surge current withstand capability of these anti-parallel diodes, which is in the order of tens of milliseconds [14]. On the other hand, the converter can be of the fault blocking type (e.g. full-bridge MMC or Alternating Arm Converter [15,16]). This type of converters can completely block the DC fault current or reduce the DC fault current to an acceptable level. Similar characteristics can be achieved by a converter without fault blocking capability in series with a HVDC breaker [17]. For HVDC breakers based on IGBTs, it is clear that the fault current must be interrupted before the IGBT operation conditions fall outside the SOA.

Second, the controllability and stability of the HVDC grid forms a constraint on the speed of the protection system. A DC side fault causes, together with an increase of fault current, a decrease of the DC voltage. This causes converters to block their IGBTs as described above. If too much converters

are in blocked state, the DC voltage cannot longer be controlled, causing outage of the entire HVDC grid. In 18, a criterion for the stability of the HVDC grid against large disturbances is given (in this case outage of a converter). Fault clearing times in the order of tens of milliseconds were given.

3.2. AC Side Constraints

Similar to AC faults, the fault must be cleared timely to avoid loss of synchronism of the generators in the grid 19. This time is referred to as the “critical clearing time” and is typically in the order of 100s of milliseconds. In case converter topologies without DC fault blocking capability are used, the AC side feeds in fault current through the converter anti-parallel diodes. The amplitude of this fault current is largely determined by the strength of the AC system at the converter point of coupling. If converter topologies with fault blocking capability are used, the converter can continue to provide reactive power support to the AC grid 16.

3.3. DC fault current

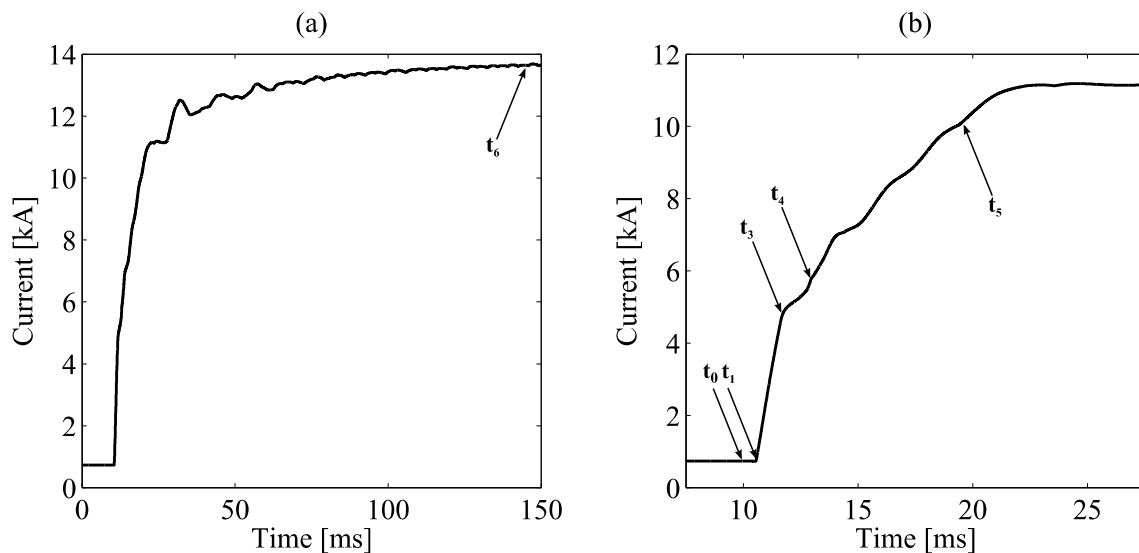


Fig. 1 DC fault current in four-terminal meshed grid 20.

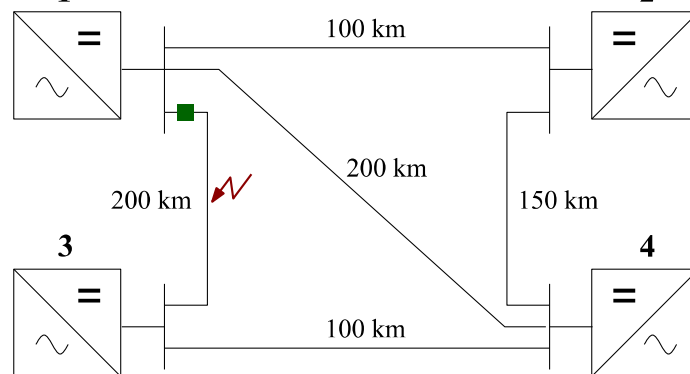


Fig. 2 Fault in meshed HVDC grid.

Fig. 1 shows an example of a DC fault current in the four-terminal meshed HVDC grid of Fig. 2, for which the parameters are given in 21. The four-terminal meshed HVDC grid is a cable-based system, where each cable is terminated by series inductors. The converters in the system are half-bridge modular multilevel converters. The fault occurs in the middle of the link between converter 1 and 3 at time t_0 and reaches the terminal 1 at t_1 . The time delay between t_0 and t_1 is caused by the finite speed of a wave traveling over the cable. After t_1 , the DC fault current increases quickly, but its rate of rise is limited by the series inductors. In the first milliseconds, successive reflections (e.g. at t_3) occur, caused by waves traveling over the line between the relay and fault location. Furthermore, other terminals start to feed in fault current. At t_4 , converter 1 blocks its IGBTs and the fault current is fed by the AC side. At t_5 , all converters in the system are blocked. Eventually, after t_6 , the fault current tends to a steady-state.

4. HVDC PROTECTION SYSTEM COMPONENTS

Based on the fault clearing strategy, the HVDC protection system must meet the constraints specified above. The most stringent requirement is the speed of operation 2. The time at which fault clearance starts, t_c , is given by:

$$t_c = t_d + t_i + t_o \quad , \quad (1)$$

in which t_d is the time for the protective relaying algorithm to detect and identify the fault, respectively, and t_o is the time at which fault current interruption starts (after receiving a tripping signal). The first two time intervals depend on the protection algorithm and determine the relay operation time. The latter time interval depends on the method of fault current interruption.

4.1. Fault current interruption

First, the fault current can be interrupted by using the converter AC breakers 10. This method of fault current interruption requires several cycles of the fundamental AC frequency to operate, breaking the current only after tens of milliseconds. Furthermore, this method results in non-selective fault current interruption at the DC side.

Second, converters with fault blocking capability can be used to interrupt the DC fault current 15, 16. The converters can be blocked within microseconds upon fault detection, leading to faster fault current interruption than the previous method. However, this method also leads to shutting down the full HVDC grid.

Third, HVDC breakers can be used to interrupt the DC fault current. Power electronic breakers are able to interrupt fault current within a millisecond or faster, but have high on-state losses [1]. Hybrid HVDC breakers have been found to give fast interruption times, while giving acceptable on-state losses. However, only prototypes have been tested and reported until now, giving opening times in the order of 2 to 5 ms 22,23. Mechanical circuit breakers can have higher fault current interruption capabilities. Currently reported mechanical circuit breakers have interruption times in the order of 5 to 10 ms 24,25. For all HVDC breakers, series inductors are needed to limit the rate of rise of the fault current. However, this increases the energy that the DC breaker has to deal with during fault clearance.

Together with fault current interruption equipment, fault current limiters can be used. These fault current limiters (such as inductors or superconducting fault current limiters) can extend the time available for the fault detection or enable the use of slower fault clearing equipment.

4.2. Protective relaying algorithms

The protective relaying algorithms must detect and identify the fault within a very short amount of time. As the time scale of the HVDC grid protection is 10 to 100 times shorter than for AC grid protection, new relaying algorithms are needed. Similar to AC grid protection, these relaying algorithms can be divided into non-unit and unit protection methods.

Non-unit protection makes use of open protection zones, which are only at one side clearly determined. They make use only of measurements local at the relay, which enables them to be fast. Several non-unit protection methods for HVDC grids have been proposed in the literature 3, 4, 5.

Unit protection is based on closed protection zones and require communication between the relays at both ends of the protection zone. Unit protection methods are inherently selective, but suffer from the time delays caused by communication. In AC grid protection, communication delays are typically in the order of 10 ms 26.

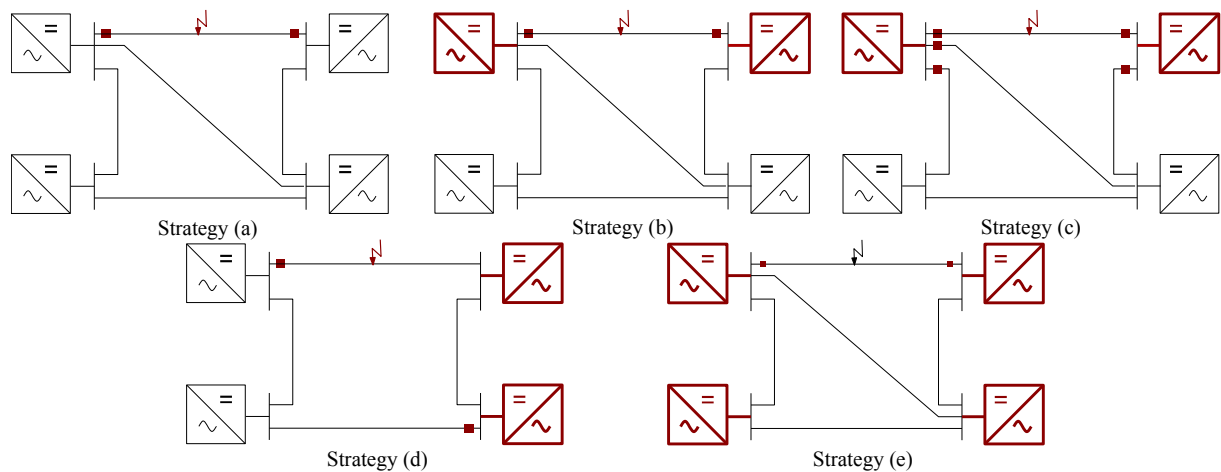


Fig. 3 Fault clearing strategies in example HVDC grid. Bold red lines indicate HVDC grid elements involved in fault clearing.

5. FAULT CLEARING STRATEGIES FOR HVDC GRIDS

Based on the above discussion on HVDC grid protection objectives, requirements and constraints, several fault clearing strategies can be defined. Fig. 3 shows possible fault clearing strategies in the HVDC grid. Below, a definition of these fault clearing strategies for HVDC grids is given. Note that only primary protection is treated in the discussion, whereas backup protection should be provided in case of failure of any part of the equipment involved in fault clearing.

5.1. Strategy (a): “line protection”

For this strategy, fault currents are interrupted by breakers at the end of the faulted line. To minimize the impact of a disturbance on the grid, a fault must be cleared before any converter in the HVDC grid blocks. Therefore, fast DC breakers at the end of every transmission line are needed in combination with non-unit protection. The time before a converter blocks is limited to several milliseconds (Fig. 2). To extend the time before the converter blocks, additional fault current limiting might be needed.

5.2. Strategy (b): “line+ protection”

For strategy (b), blocking of converter IGBTs of the converters at the buses terminating the faulted line is allowed. If the converter is of fault blocking type, this diminishes the current that the breakers must interrupt. The time constraint for fault clearing is relaxed compared to strategy (a). However, the fault must be cleared timely to avoid collapse of the full HVDC grid, limiting the time constraint to a few tens of milliseconds.

5.3. Strategy (c): “open grid protection”

All breakers and converters at a bus adjacent to the faulted line co-operate to interrupt the DC fault current. After fault current interruption, the breakers in the healthy lines reclose to restore normal operation of the grid. For this strategy, stability of the HVDC grid is also the limiting factor for interruption of the fault current. The protection system must now open and reclose breakers within this limited timeframe. Therefore, constraints on the protective relaying algorithm are more stringent than for the previous strategy.

5.4. Strategy (d): “grid-splitting protection”

In this strategy, the DC grid is split up in different protection zones. The strategy consists of two stages; first the faulted zone is swiftly isolated from the healthy part of the grid. Second, the faulted line is isolated within the faulted zone. The first part of strategy d requires fast protection and fast breakers. The time constraint is here imposed by the converter IGBTs of the healthy part of the grid. For the second part of strategy (d), the time constraint is either imposed by the converter diode surge withstand capability or ac system stability, which allows slower fault clearing.

5.5. Strategy (e): “low-speed HVDC grid protection”

The entire HVDC grid is affected in case of faults. A first option is to clear the fault by actions at all converters in the network. This strategy is limited to small DC grids, where the impact of switching of the HVDC grid on the AC grid is tolerable. A second option is to limit the fault current infeed of the converters, which enables the use of slower protective algorithms and breakers. For this option, the HVDC grid is not completely switched off, which enables faster fault recovery. The time constraint for this option is determined by the AC network constraints.

5.6. Summary

Fig. 4 summarizes the time scales for the fault clearing strategies together with time scales for implementation of these fault clearing strategies using the HVDC grid protection equipment described above. These time scales are compared against the constraints for the protection system as described in Section 3. The time periods for the constraints are indicative and have been chosen to comply to certain sets of DC faults (e.g. converter blocking for close faults occurs faster than for remote faults). The times for the protective relaying algorithms (t_d+t_i) and for the fault current interruption methods (t_b) are given in Table 1.

It is clear that each fault clearing strategy complies to different constraints and hence complies to different objectives for HVDC grid protection. If large disturbances in the HVDC grid are not allowed or must be minimized, strategies (a), (b) and (c) can be applied. These strategies focus on limiting the extent of a disturbance in the HVDC grid by clearing the fault locally. They mainly rely on fast acting fault clearing equipment in combination with fast relaying algorithms. To reduce the stringent requirements on the breakers or on the relaying algorithm, fault current limiters can be used.

By contrast, if the HVDC grid on itself is not the priority, strategies (d) and (e) can be applied. For these strategies, a larger part of the HVDC grid can be affected during or even after fault clearance.

For strategy (d), fast breakers are needed to first split the grid. For the second part of strategy (d) and for strategy (e), the requirements on fault clearing equipment are less stringent.

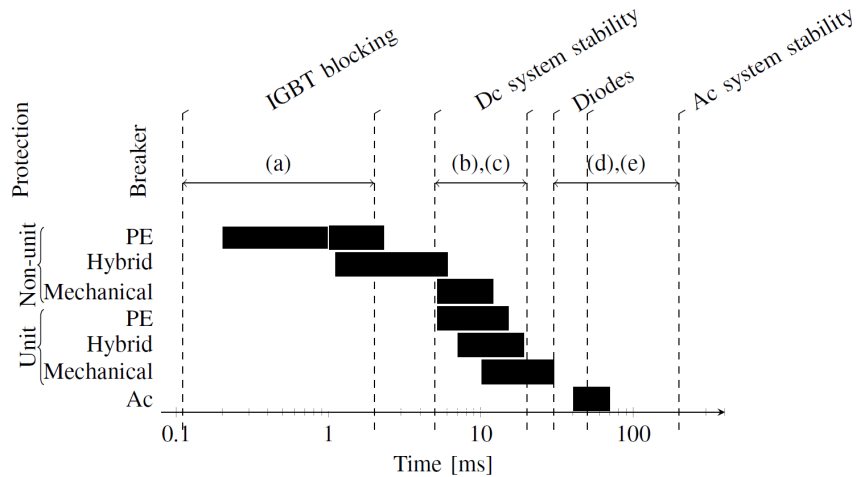


Fig. 4 Time scales for fault clearing strategies and HVDC grid protection equipment

Table 1 Time scales for protection method and methods of fault current interruption (based on currently reported equipment)

Protection Method	Time (t_d+t_i)
Non-unit protection	0.1-2 ms
Unit protection	5-10 ms
Fault current interruption	Time (t_b)
Power Electronic (Breaker, Converter)	0.1 ms
Hybrid Breaker	2-5 ms
Mechanical Breaker	5-10 ms
AC Breaker	40 ms

6. CONCLUSION

This paper provides a definition and classification of fault clearing strategies for HVDC grids. The fault clearing strategy for DC faults depends on the objectives of HVDC grid protection. If the objective of HVDC grid protection is to protect the HVDC grid itself, stringent time constraints are imposed by the power electronics and HVDC grid stability. Therefore, a fast protective algorithm and fault clearing method is needed, which limits the extent of a disturbance in the HVDC grid. When the focus of the HVDC grid protection lies on minimizing disturbances to the AC system, fault clearing times can be longer. For these strategies, a larger part of the HVDC grid can be affected during or even after fault clearance.

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